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PHYSICAL CHARACTERISTICS OF BONE

HAROLD M. FROST, M.D.

INTRODUCTION

The behavior of human, living bone under diverse conditions has long interested, puzzled, and frustrated investigators. Many examples of peculiar skeletal behavior occur which cannot be understood. Some examples, in brief listing are: recurrence of angulation in greenstick fractures which are not completed; compression failure in some greenstick fractures; bowing of weight bearing long bones in osteomalacic diseases; brittle nature of fractures in aged patients; migration in vivo of many endoprotheses and metallic fixation devices; Otto pelvis; pathological fractures in hypercortisonism; aseptic necrosis of the femoral head; Looser's zones of transformation; march fractures.

A great deal has been learned about the gross characteristics of human bone through study by methods in use in materials engineering. The poor reproducibility of such measurements means that undetected variables are plaguing the investigator. To better understand the whole it therefore becomes necessary to understand the parts of the whole. *This means that attention must be diverted for the time being from the macroscopic and turned to the microscopic.*

In studying the microscopic behavior of bone under load it becomes necessary to combine the methods and knowledge of diverse disciplines. These disciplines include metallurgy, solid state physics, chemistry, structural engineering, materials engineering, histology and physiology. It is also necessary to keep in mind during such studies that the biological side of bone affects the structural side and vice versa. This mutual interaction complicates the problem considerably. Until the attack on the problem has dug deeply enough it is inevitable that mistakes in interpretation of data and in design of experiments will occur. This is part of the growth in knowledge and must be cheerfully accepted.

The following brief series of papers dealing with the physical characteristics of bone are more tantalizing than informative. The observed results raise many more questions than they answer — an indication that the road ahead is a long one.

The bibliography follows Part IV of this series.

PHYSICAL CHARACTERISTICS OF BONE — PART I

THE EXISTENCE OF PLASTIC FLOW IN VITRO

HERBERT ROTH, B.A., HAROLD M. FROST, M.D. AND ANTHONY R. VILLANUEVA, B.S.

INTRODUCTION

Elastic behavior and plastic flow are terms used by metallurgists. When a slightly bent steel wire returns to its original shape and dimensions upon release of the bending force it is exhibiting elastic behavior. If the wire is bent too much it will retain some of the bend. In the region of the wire where the kink occurs there has been a sliding of ultramicroscopic planes of crystals, phase boundaries and dislocations. This sliding is termed plastic flow.

Most solids, glass being an exception, have a crystalline structure. The crystals are of microscopic or ultramicroscopic dimensions and are physically oriented to varying degree with respect to their neighbors. In some materials, such as table salt, the orientation is highly regular, while in others, such as cast iron, the orientation is highly irregular. The difference may be illustrated by the analogy of the disorder present in a pile of bricks dumped on the ground, and the order present after a mason has constructed a fireplace out of them.^{2,10}

The various crystals, phases or domains in a structural material adhere to one another by the action of surface bonds of several types. All of these bonds are basically electrical in nature. Springing of these bonds occurs during elastic behavior. Rupture of the bonds occurs during plastic flow, the ruptured bonds reattaching at new sites during the plastic flow.

When plastic flow has occurred a permanent deformation of the material results. This permanent deformation is termed a permanent set.

The actual events during elastic deformation and plastic flow in various materials are usually complex due to microscopic and ultramicroscopic degrees of disorder, differences in composition, corrosion, and other factors. To understand the microscopic events in a material under load it has been necessary to develop and apply analytical methods which reveal microscopic and ultramicroscopic phenomena.^{2,5,6,10,11}

Simple experiments are now described which demonstrate that plastic flow may occur in fresh, wet, human bone.

MATERIALS

Two tibias and two femurs were obtained fresh from the operating room, the amputations being done for soft tissue neoplasm in one case and vascular insufficiency in the other. The specimens were kept moist before and during the experiments with tap water applied by suitable means. The patient's ages were 18 and 63 years.

METHODS

Test samples were sawed from the diaphyseal cortices with a fine toothed hack saw and ground with surfaces flat and parallel under running water.⁷ Finished samples

were about 10 x 5 x 5 mm and cut so that any of the major axes of the diaphysis were parallel to one of the sample faces. Loads could thus be applied parallel to the longitudinal, radial, and tangential axes.

Test devices were utilized to apply the loads. There were two types.

A) A ram and anvil were machined from mild steel, the ram being a key 3 mm. in width, the anvil containing a slot for the key 0.1 mm. larger in width than the key. (Fig. 1). Ram and anvil were positioned in a vise in such manner that they fitted together when the jaws were closed. A specimen placed between the jaws is squeezed between them. Shear load was applied in the plane connecting the homologous sides of the anvil and ram.

B) The second device was simpler. A dissecting needle was laid with its long axis on the surface of the test sample and the vise jaws closed, squeezing the needle into the substance of the test sample. (Fig. 2). The forces developed in the bone in contact with the needle were complex.

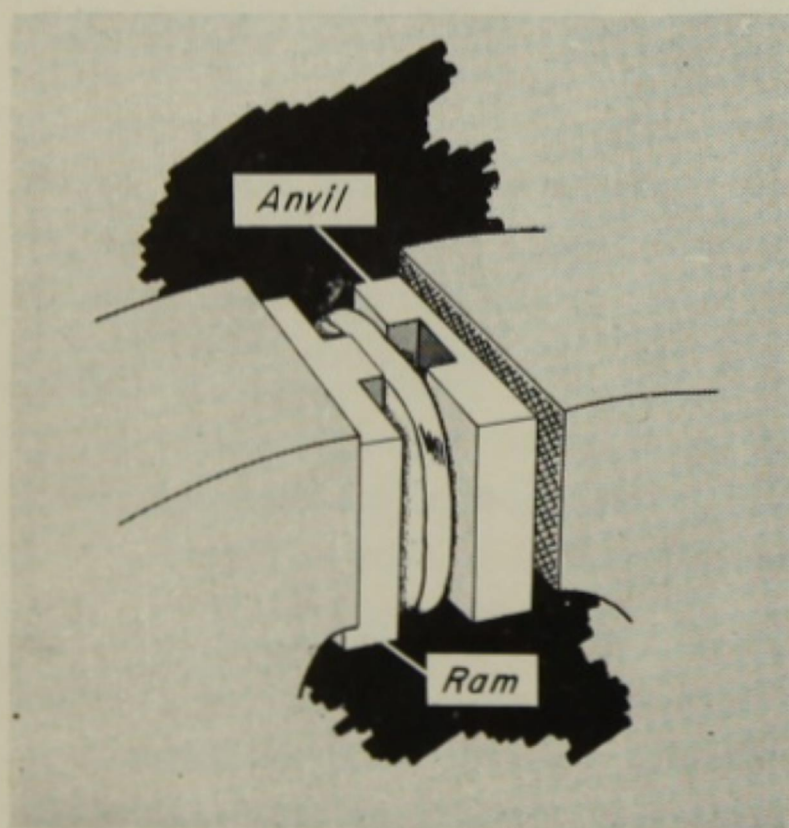


Figure 1

The arrangement of the vise, ram, test specimen, and anvil are illustrated. The ram is a key machined into a block of steel. The anvil contains a slot into which the ram fits.

In use the ram and anvil were glued to the vise jaws with an adhesive. Test samples were then clamped between them and kept moist either with a medicine dropper or with a wick connected to a large reservoir of water.

The plane of idealized shear is parallel to the sides of the ram and anvil and connects the sides through the substance of the test sample.

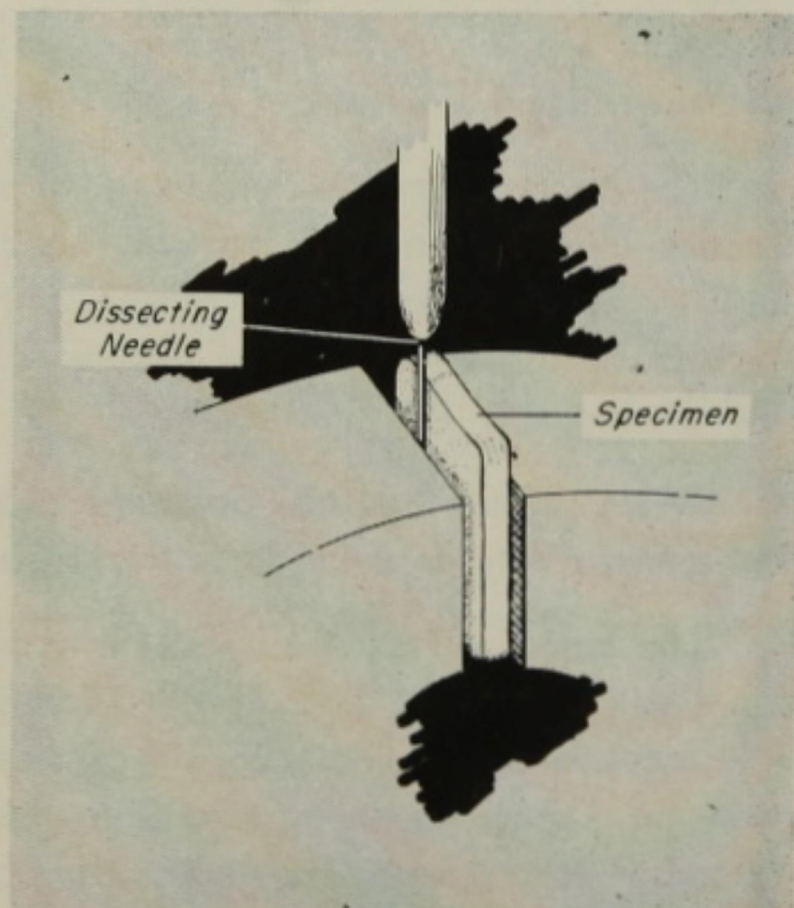


Figure 2

The arrangement of the vise, ram, test specimen and anvil when a dissecting needle is used as a ram is illustrated. The stresses produced in the test specimen in this set-up are complex and no effort is made to describe them.

The test samples were kept moist with tap water before and during the experiments. After the experiments some samples were dried and mounted intact on microslides. In other samples thin, undecalcified sections were made in such a manner that the

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surface indentation in the original test sample lay along one of the edges of the finished sections. The sections were then stained with basic fuchsin by methods described elsewhere.⁸

OBSERVATIONS

A) Quantitative measurement of the forces applied is not possible with the present experimental design.

B) Test samples loaded lightly would visibly indent in front of the two rams. Upon removal of the load the indentation completely disappeared, leaving perfectly flat surfaces with no visible evidence of damage.

C) Test samples heavily loaded developed larger indentations under load. Upon removal of the load some of the indentation remained in the surfaces of the test samples. The shape of the indentations was a mirror image of the shape of the rams. (Fig. 3).

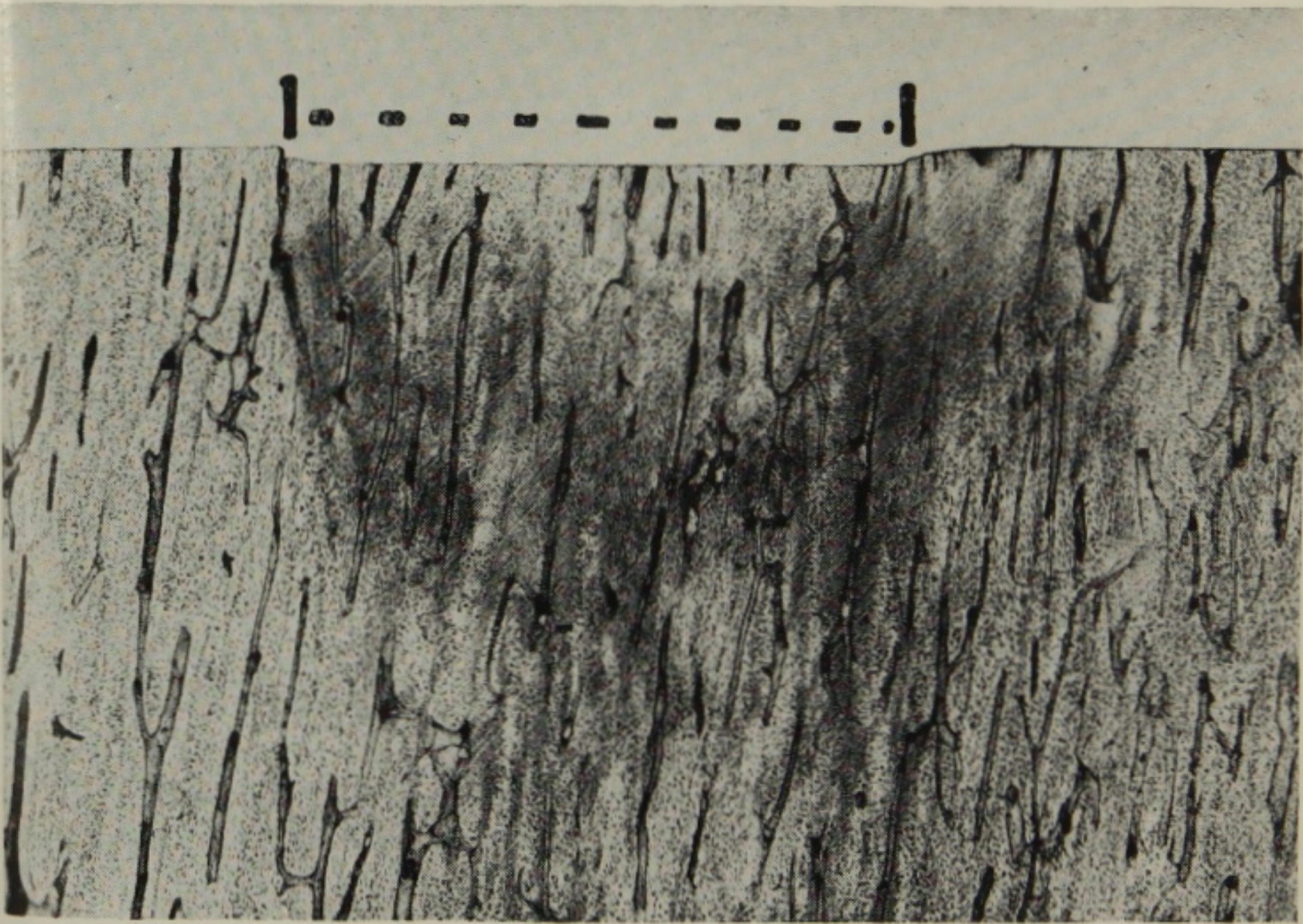


Figure 3

26x. Photomicrograph of section cut through a test specimen given a permanent set by the ram in figure 1. An india ink line delineates the indentation representing the permanent set. Plastic flow had to occur to permit this permanent set.

D) Test samples loaded too heavily fractured in the vise. In the case of the device in Figure 1, the failure was grossly a shear failure, a rectangular piece of the sample being fractured and forced into the slot in the anvil. In the case of the device in Figure 2, the failure was a tension failure, the needle acting as a wedge

which forced the sample material apart in opposite directions. The amount of load increase required to fracture the sample over the amount of load required to produce a permanent set was small in comparison to the total load range within which the material remained intact and did not fracture.

E) Permanent sets could be given to samples loaded in any direction.

Figure 3 is a photomicrograph of a section cut through the surface of a test sample given a permanent set by the device in figure 1. The mirror image of the ram appears along the upper edge of the section as an indentation.

F) In some of the tests samples were left clamped between anvil and ram for prolonged periods of time with loads insufficient to break them or to produce a permanent set within the few minutes required for the experiments described above. The prolonged loading elicited some unusual effect from the sample because often, after many hours, they would suddenly fracture with a readily appreciated loud snap.

DISCUSSION

The preceding experimental description leaves no doubt that plastic flow of some sort can occur in fresh, human, wet bone. A permanent set results from the plastic flow. In a rough way it can be stated that the amount of load necessary to produce plastic flow in short time periods is so close to the amount of load needed to produce failure that plastic flow is probably not normally a skeletal physiological problem. The large range of elastic behavior underlying the point at which plastic flow occurs probably encompasses normal daily skeletal loads.

In children's bones sustaining fractures a permanent set as the result of plastic flow would be even more likely to occur than in adult bone. This is because children's bones contain less mineral per unit volume than adult bone and are accordingly more flexible. The recurrence of angulation in greenstick fractures which are not completed could be explained by the presence of a permanent set. Such a permanent set could be "unset" as a rule only by completing the fracture.

The hours-delayed failure of specimens clamped in the vise for prolonged periods suggests two other factors familiar to metallurgists: creep and fatigue. Creep is a gradual yielding of a structural material under load, such as the sag that develops in the girders of a bridge after 30 years of service. Fatigue is a failure resulting from normal loads rather than excessive loads, and is a complex topic. Additional work will be needed to follow up these suggestions.

SUMMARY

Plastic flow and a permanent set can be produced in fresh, wet, human bone.